# Inhomogeneous thermalizaiton of the quark-gluon plasma

Akihiko Monnai
(IPhT, CNRS/CEA Saclay)

QCD in Finite Temperature and Heavy-Ion Collisions
14th February 2017, Brookhaven National Laboratory, NY, USA

“hydrodynamization”?

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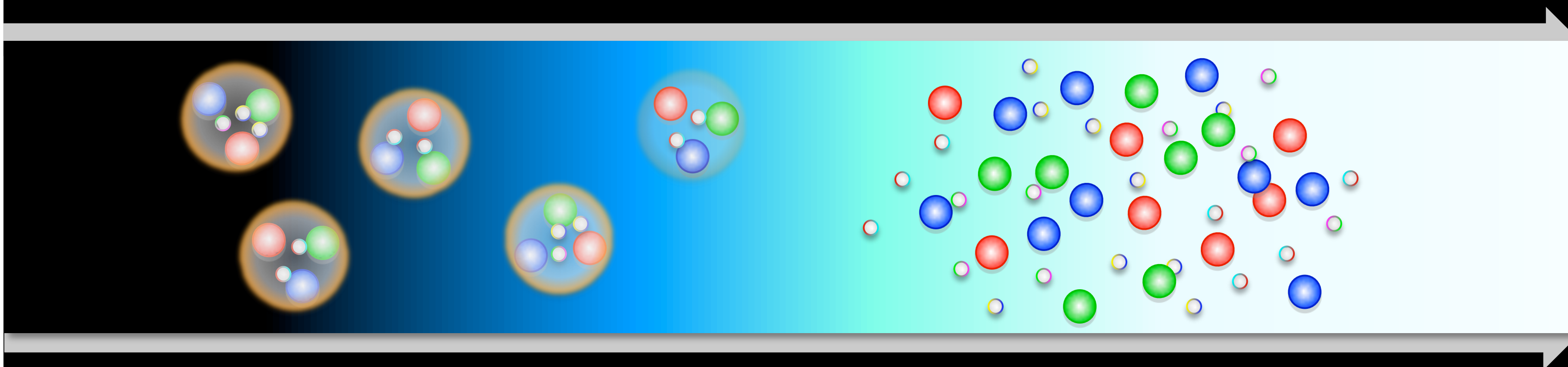
# Introduction

- The quark gluon plasma (QGP); a high-temperature phase of QCD



The QGP created in high-energy heavy-ion collisions is quantified as a relativistic fluid with extremely small viscosity

⇨ The onset of hydrodynamic stage is one of the most controversial issues

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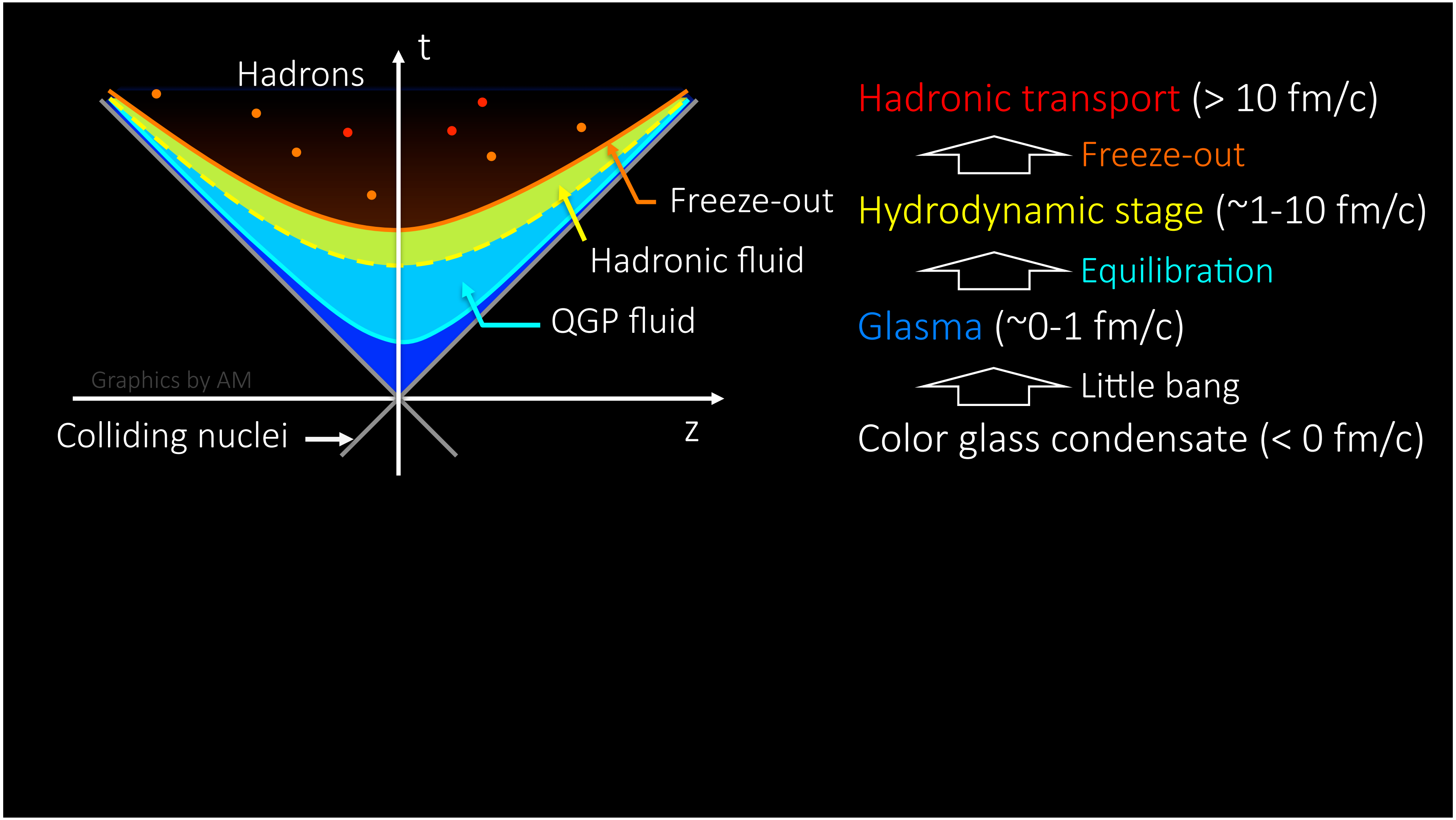
- A standard model of heavy-ion collisions



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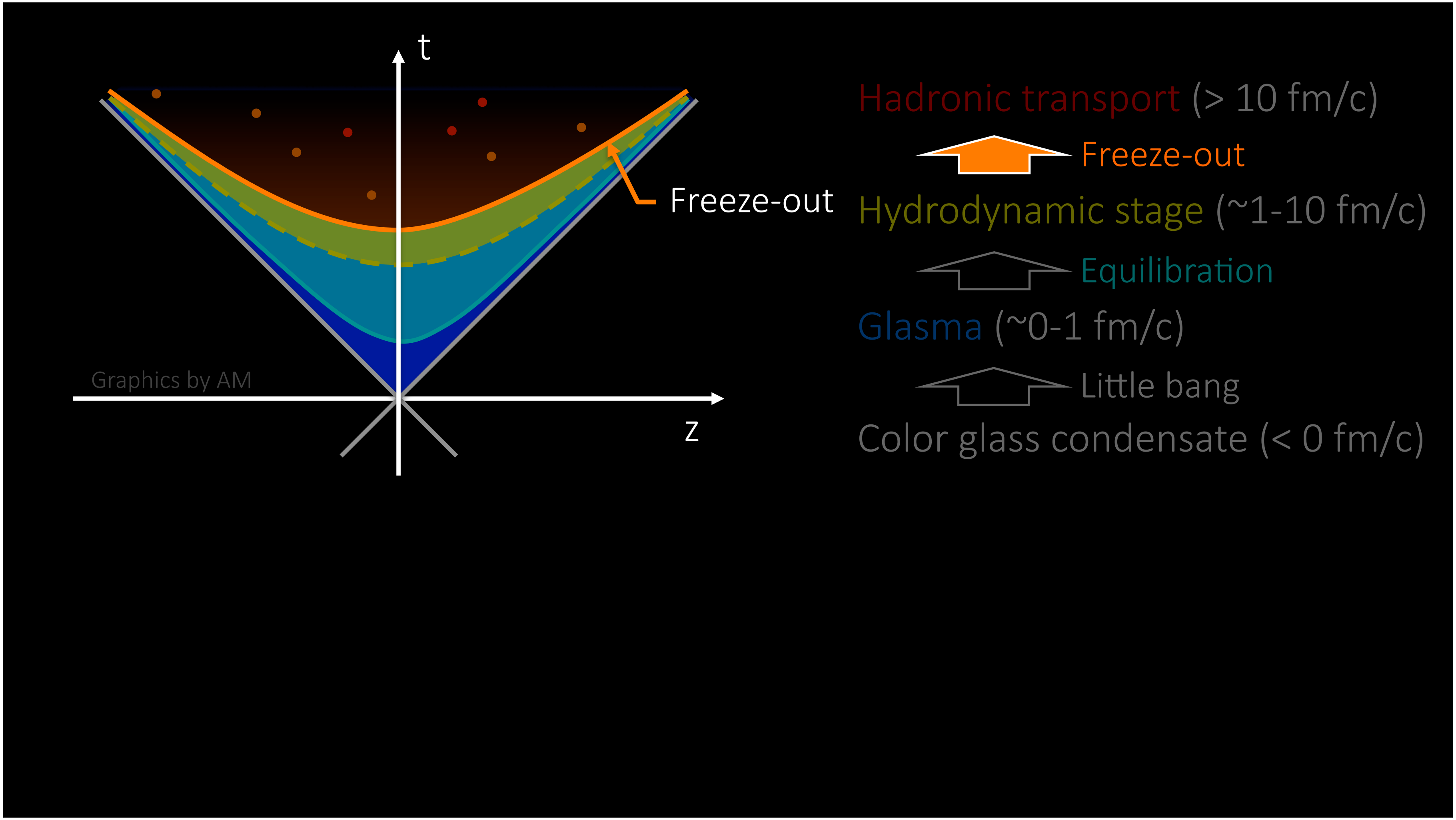

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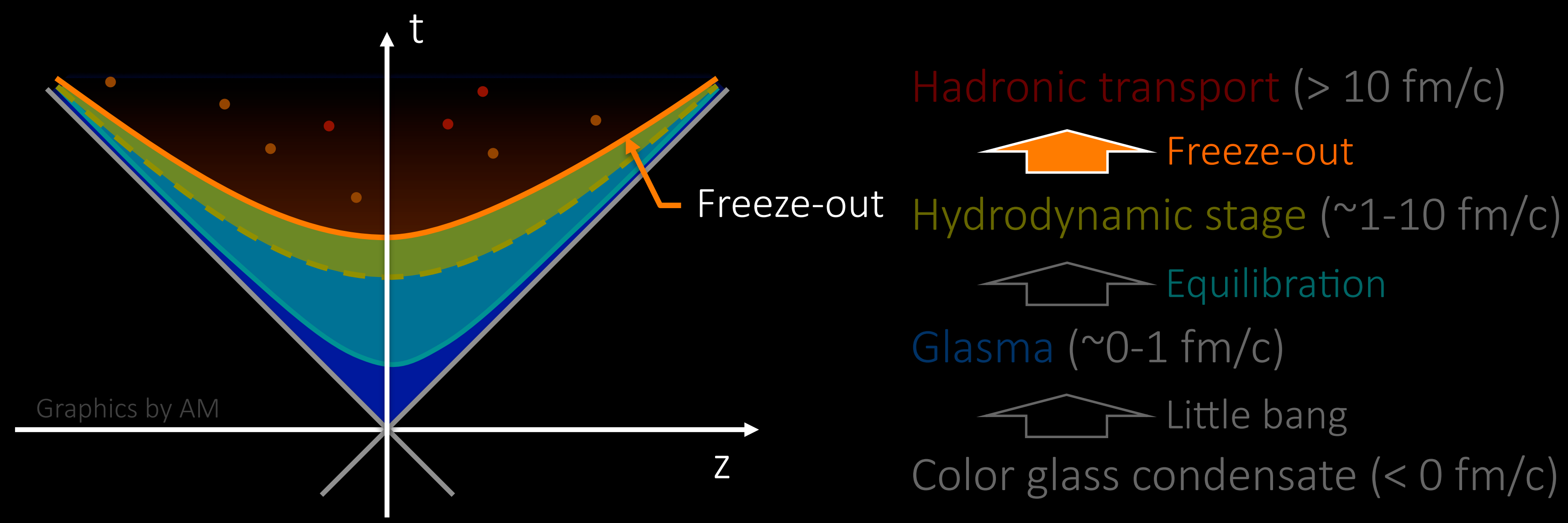


▶ Thermal freeze-out uses a position-dependent hypersurface $\Sigma_f$

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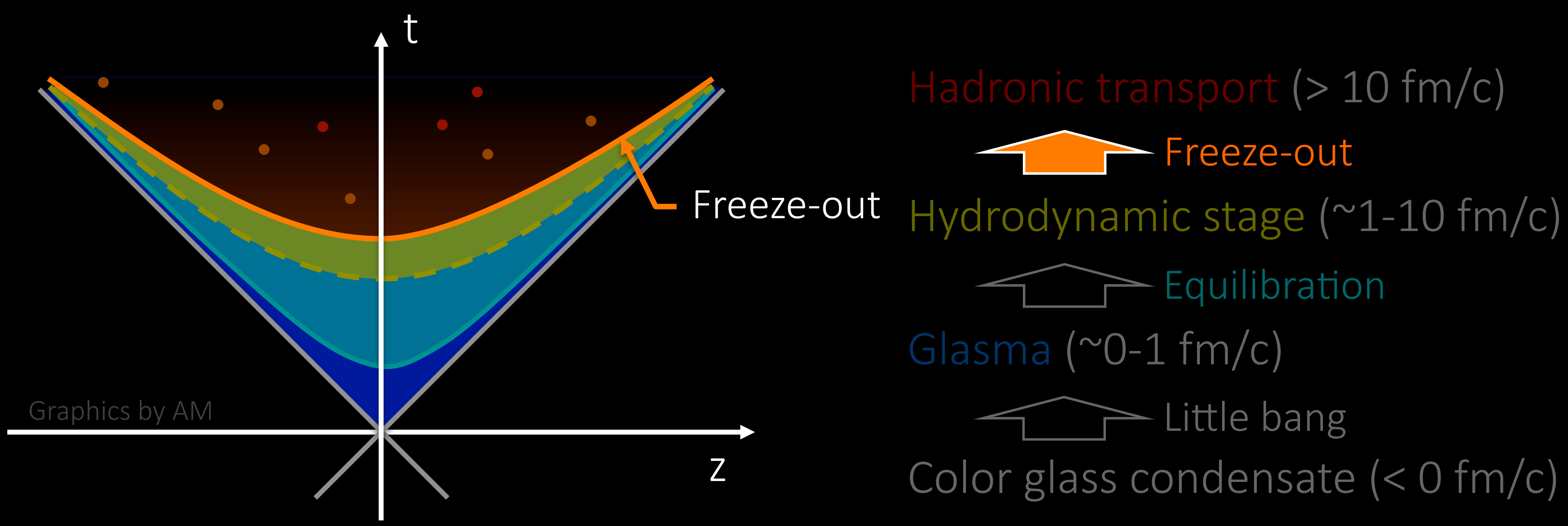


- Thermal freeze-out uses a position-dependent hypersurface $\Sigma_f$
- Chemical freeze-out is determined by a T-$\mu_B$ (and thus position) dependent criterion

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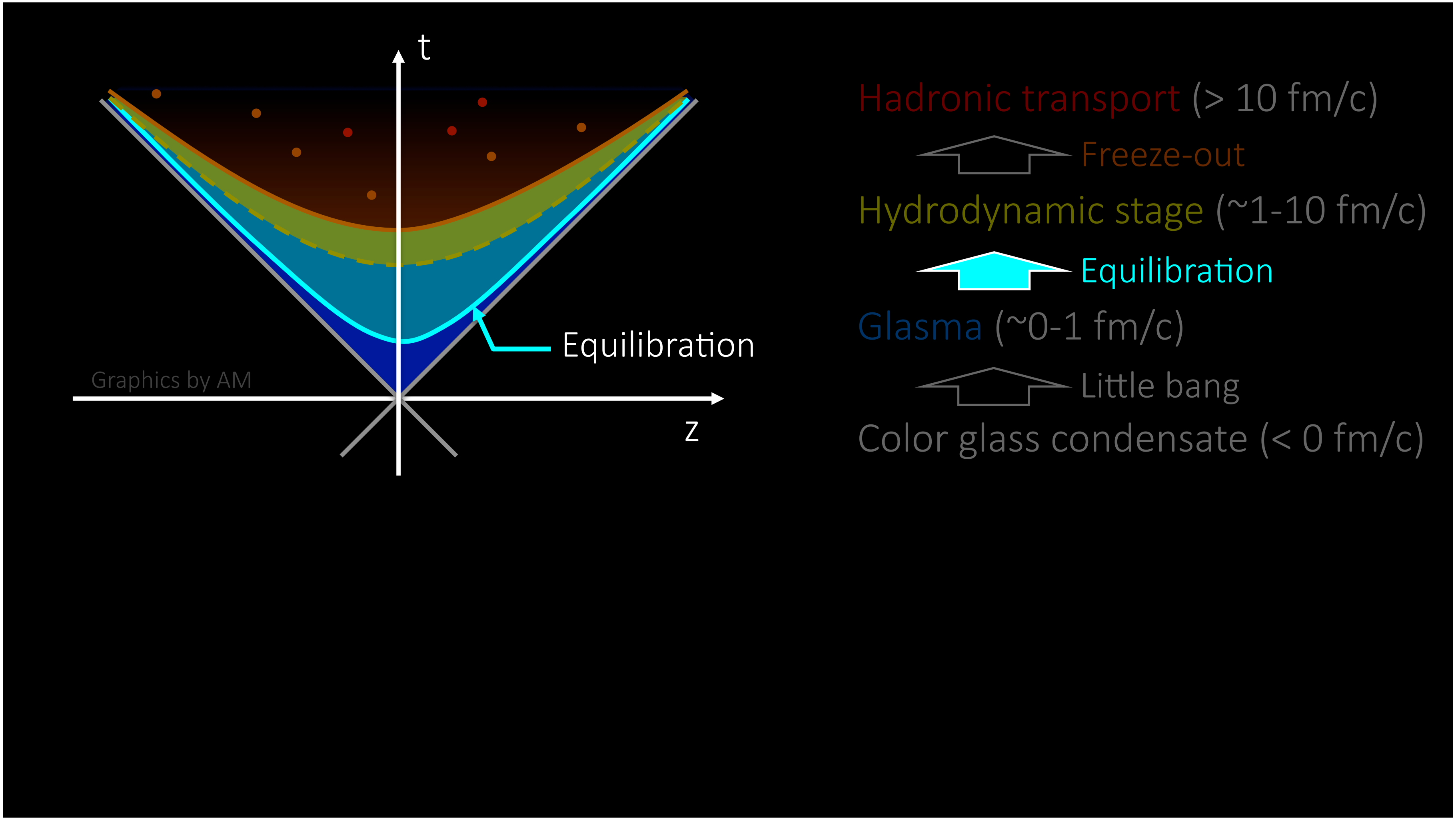

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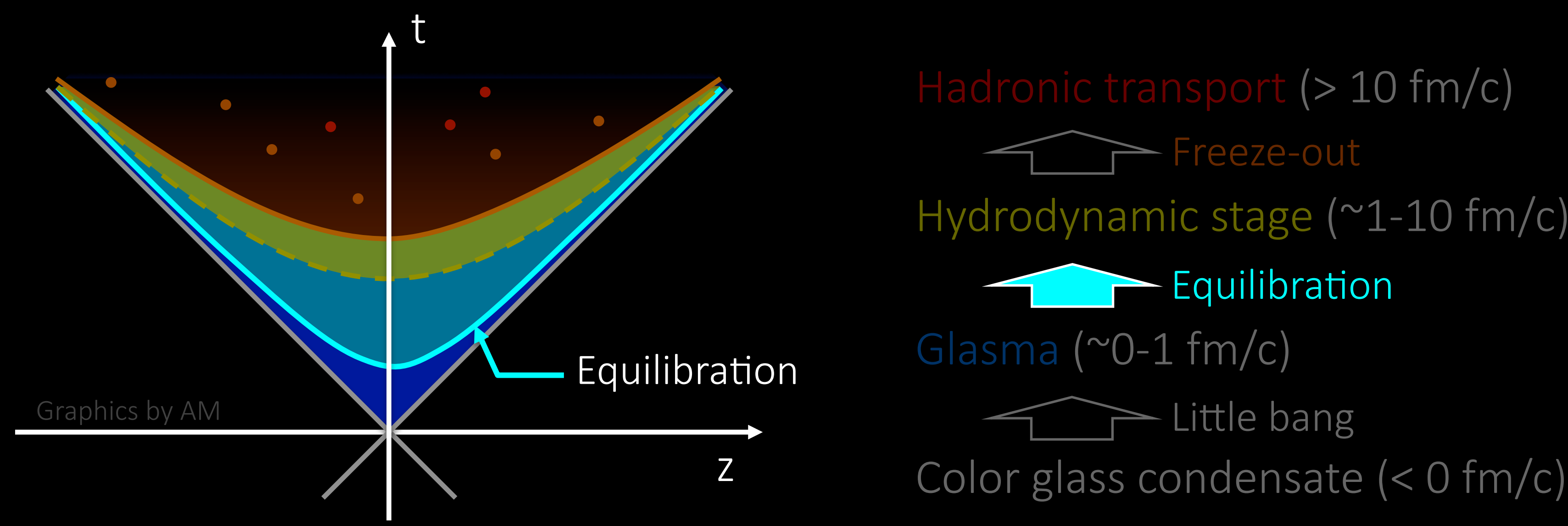


▶ Thermal equilibration is set by a position independent initial time $\tau_{th}$

Discussed w/ AdS/CFT: Balasubramanian et al., PRL 111, 231602; JHEP10, 082

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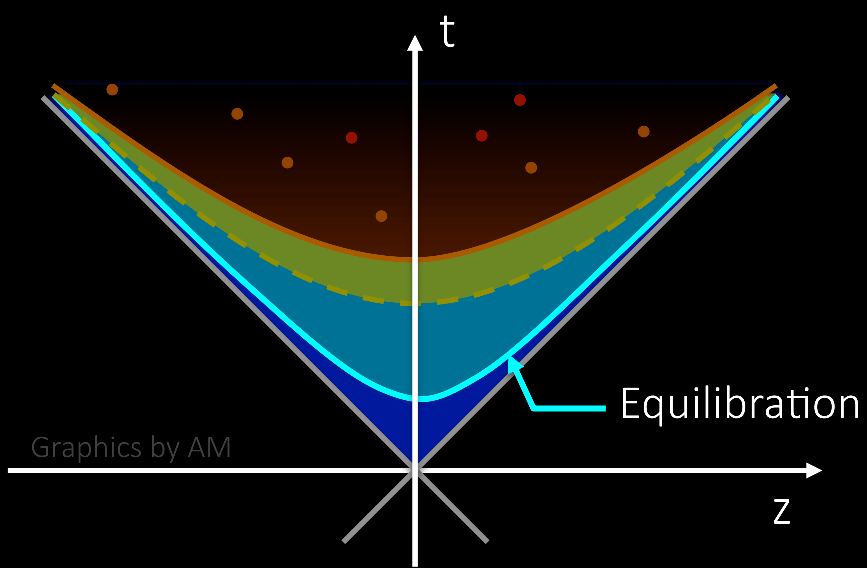



Hadronic transport (> 10 fm/c)

Freeze-out

Hydrodynamic stage (~1-10 fm/c)

Equilibration

Glasma (~0-1 fm/c)

Little bang

Color glass condensate (< 0 fm/c)

- Thermal equilibration is set by a position independent initial time $\tau_{th}$

  Discussed w/ AdS/CFT: Balasubramanian et al., PRL 111, 231602; JHEP10, 082

- Chemical equilibration is often neglected; determined by position-dependent rate equations

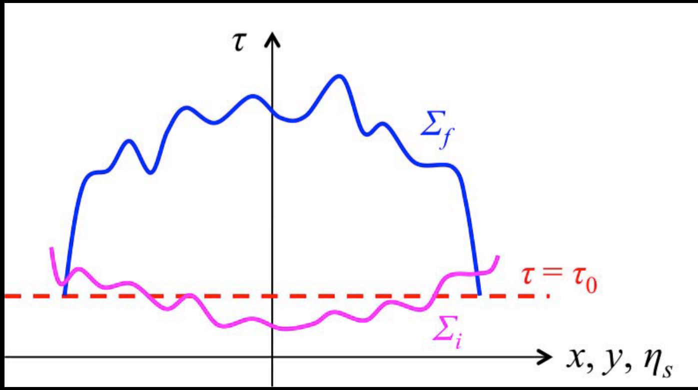
  Gelis et al., JPG 30, S1031; AM, PRC 90, 021901

# Motivation

- Is it a good assumption?

▶ Introduce the initialization hypersurface $\Sigma_i$

- E.g. forward rapidity & peripheral edges may thermalize slower



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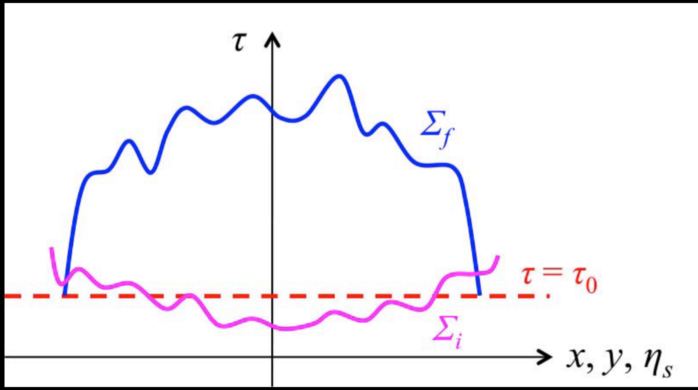



▶ Suppose equilibration is controlled by a typical momentum $p$

$$p \sim T_{\mathrm{eff}} \sim e^{1/4}$$

Cf: Kurkela and Moore, JHEP 12, 044
Kunihiro, Mueller, Ohnishi, Schaefer, Takahashi, Yamamoto PRD 82, 114015

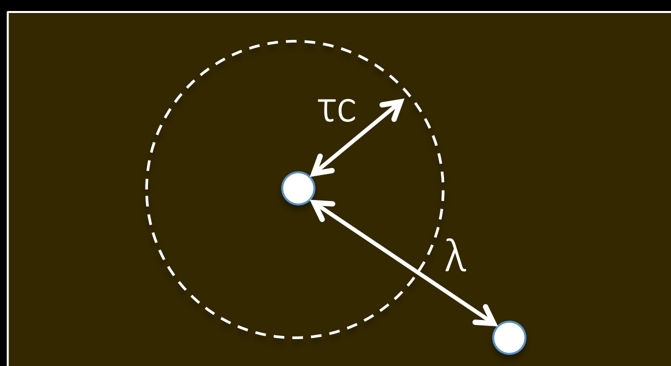
Non-expanding systems: $\tau_{\mathrm{th}} = Ce^{-1/4} + \tau_0$

Expanding systems: $\int_{\tau_0}^{\tau_{\mathrm{th}}} e^{1/4} d\tau = C$ ⇨ Definition of $\tau_{\mathrm{th}}(x)$

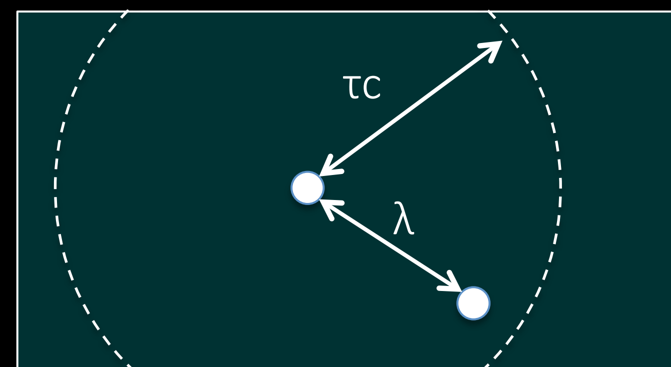
# The time scale

- A naïve particle picture

▶ Causality - mean free path $\lambda$ vs. proper time $\tau$




If $\tau < \lambda$, the constituents do not know the spatial configuration




If $\tau > \lambda$, the constituents can interact; the pressure develops

▶ Viscosity $\eta = np\lambda/3 \sim T_{eff}s\lambda/4 = s/4\pi$ implies

$\lambda \sim 0.1$ fm for $T_{eff} = 600$ MeV and $\lambda \sim 0.6$ fm for $T_{eff} = 100$ MeV

# Model

- For a system where hydro and non-hydro regions coexist

▶ Pre-hydro EM tensor

$$T^{\mu\nu}_{\mathrm{pre}} = e u^\mu u^\nu$$

The same as the EM tensor of a non-interacting "dust"

▶ Hydro EM tensor

$$T^{\mu\nu}_{\mathrm{fluid}} = (e + P + \Pi) u^\mu u^\nu - (P + \Pi) g^{\mu\nu}$$

Dust limit w/ $\Pi = -P$

Ideal hydro limit w/ $\Pi = 0$

▶ Once the $\tau_{\mathrm{th}}$ criterion is met, switch from $T^{\mu\nu}_{\mathrm{pre}}$ to $T^{\mu\nu}_{\mathrm{fluid}}$ w/ the initial condition $\Pi = -P$ for the bulk pressure given by

$$D\Pi = -\frac{1}{\tau_\Pi}[\Pi + \zeta \nabla_\mu u^\mu]$$

*We neglect pre-flow and consider only longitudinal free streaming here

# Entropy production

- w/ the Bjorken flow

Ideal hydro phase: $\tau s = \tau_0 s_0$

Pre-hydro phase: $\tau e = \tau_0 e_0 \Rightarrow \tau s = (\tau/\tau_0)^{1/4} \tau_0 s_0$

Entropy production

If colder regions take more time to equilibrate, they are heated more

$$\int_{\tau_0}^{\tau_{\mathrm{th}}} e^{1/4} d\tau = C \Rightarrow \tau_{\mathrm{th}} = \tilde{C} {e_0}^{-4/3}$$

$$\frac{\tau_{\mathrm{th}} s(\tau_{\mathrm{th}})}{\tau_0 s_0} \propto e_0^{-1/3}$$

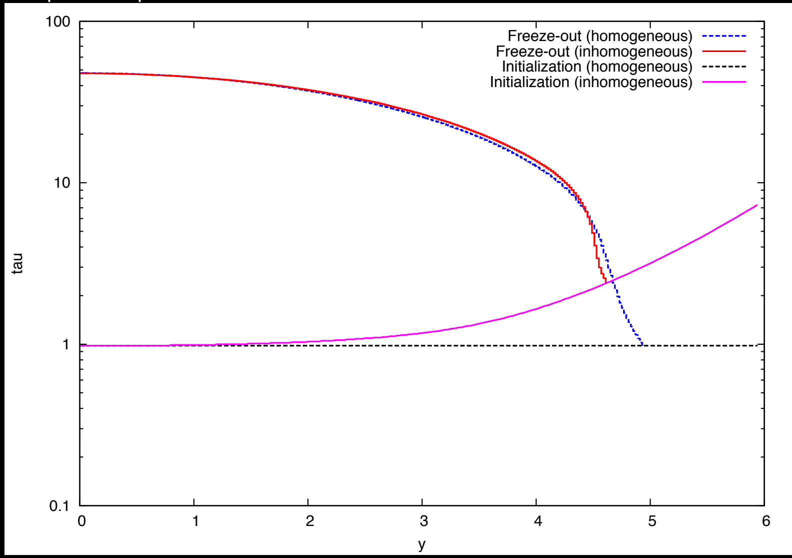
Smearing of the differences in energy density incl. fluctuations vs. the time for equilibration

PRELIMINARY

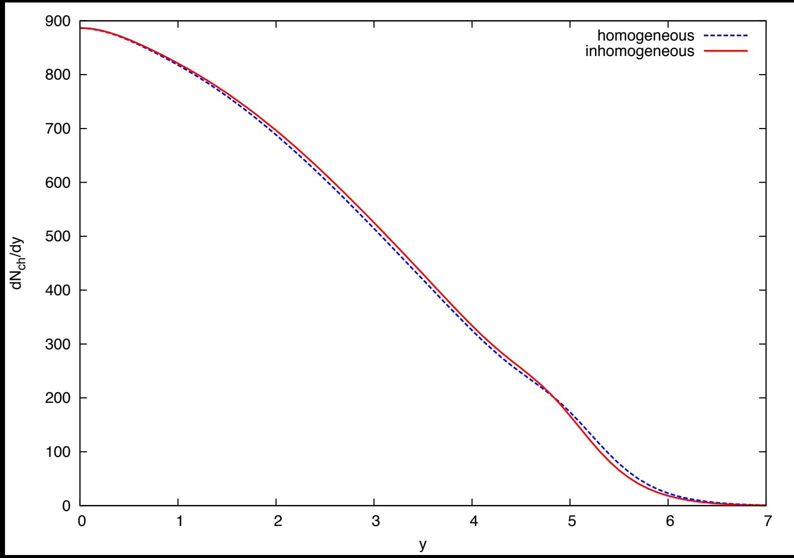
# Longitudinal dynamics

- w/ 1+1D non-boost invariant hydro and a smooth initial cond.

$\Sigma_i$ vs $\Sigma_f$




Rapidity distribution




▶ The effects on rapidity distribution is small

If true, one does not have to worry about $\tau_{th}(x)$; the effects can be minimalized as the lifetime of the QGP is longer in 1+1D

# Summary and outlook

- Effects of local initial time $\tau_{th}(x)$

  - We developed a model for the systems w/ mixed regions of hydro and non-hydro
  - The hydro-dust picture with the current $\tau_{th}(x)$ criterion suggests the effect is small, suggesting a global $\tau_{th}(x)$ is a good approximation

    - Need to remove the artifact of 1+1D evolution

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Future prospects include

- Investigation of transverse dynamics using 2+1D hydro
- Study of the effects on fluctuating initial geometries
- Introduction of more realistic pre-equilibrium models

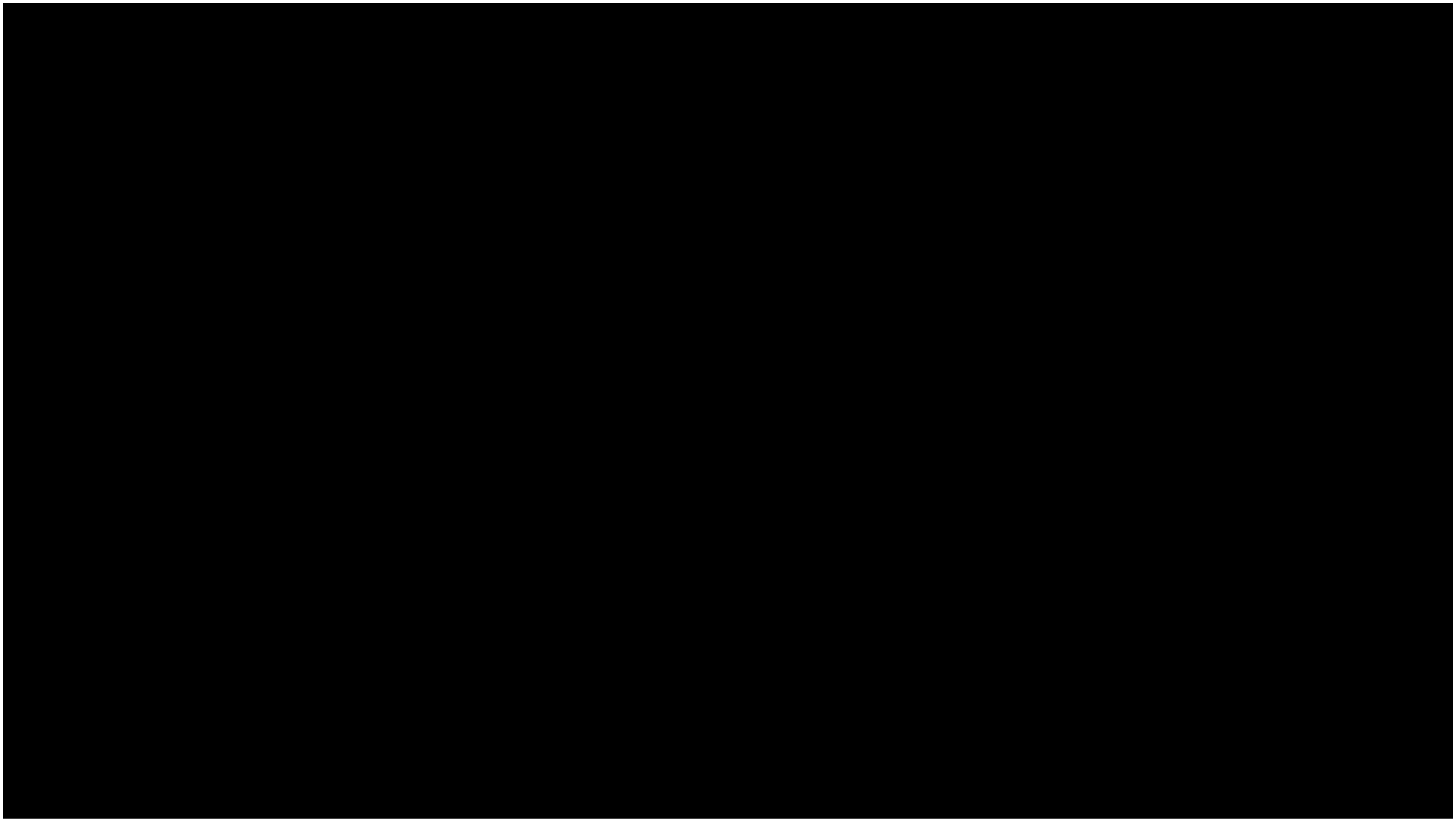
# The end

Thank you!

FORTHCOMING

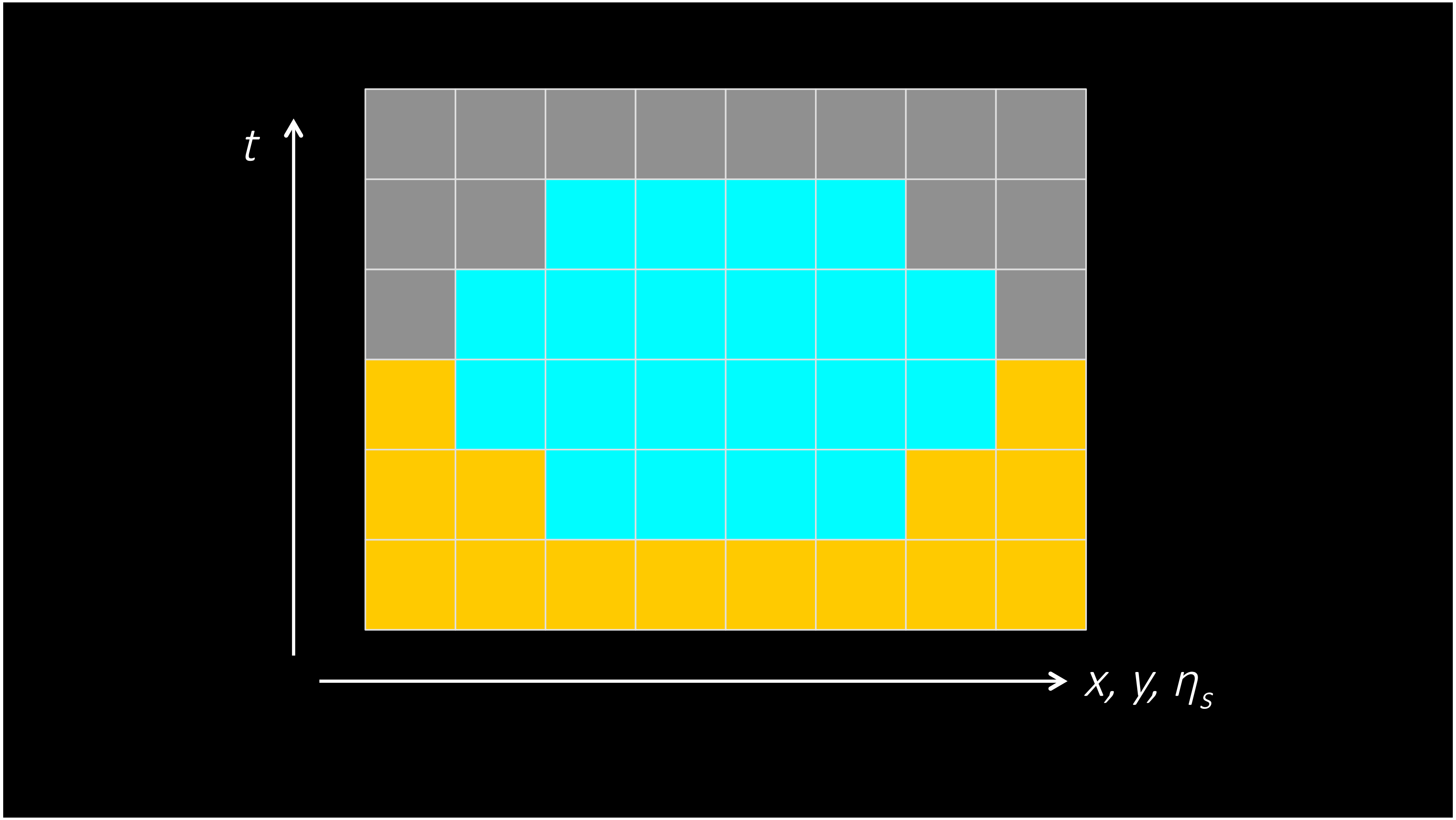
# Transverse dynamics

- w/ 2+1D boost invariant hydro



# Boundaries

- Initialization & freeze-out hypersurfaces



# Boundaries

- 6 types of boundaries

1. Fluid to particles (time-like)

   Freeze-out

2. Fluid to particles (space-like)

   Freeze-out

3. Dust to fluid (time-like)

   Π = -P prescription

2. Dust to fluid (space-like)

   Π = -P prescription

5. Dust to particles (time-like)

   Neglected

6. Dust to particles (space-like)

   Neglected